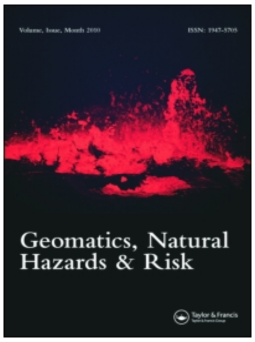

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Express Letter

Observed Ionospheric Effects of 23 October 2011 Van, Turkey Earthquake

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On 23 October 2011, a very strong earthquake with a magnitude of $\mathrm{Mw} = 7.2$ shook Eastern Anatolia, and tremors were felt up to 500 km from the epicentre. In this study, we present an early analysis of ionospheric disturbance due to this earthquake using Global Positioning Satellite-Total Electron Content (GPS-TEC). The variability with respect to average quiet day TEC (AQDT) and variability between the consecutive days are measured with symmetric Kullback–Leibler divergence (SKLD). A significant variability in total electron content (TEC) is observed from the GPS stations in the 150 km neighbourhood of the epicentre eight and nine days prior to the earthquake. An ionospheric disturbance is observed from GPS stations even more than 1,000 km to the epicentre, especially those on the North Anatolian fault (NAF). The present results support the existence of lithosphere–atmosphere–ionosphere coupling (LAIC) associated with Van, Turkey earthquake.

1. Introduction

In recent years, increased earth and space-based observations of the ionosphere indicate that there exists a coupling mechanism between seismic activities in the lithosphere and deviations or disturbances in the electron concentrations in the ionosphere, especially before strong earthquakes. These observations usually include variability in the critical frequency of the F2 layer, foF2 and Total Electron Content (TEC) (Ondoh 2000, Chuo *et al*. 2001, Pulinets 2004, Karatay 2010). With a world-wide dense network, global positioning satellite (GPS) receivers offer a cost-effective and efficient way of computing TEC compared to expensive and sparse foF2 measurements from earth or space-based ionosondes (Arikan *et al*. 2003, Nayir *et al*. 2007). TEC is defined as the line integral of electron density on a path joining the satellite and the receiver (Arikan *et al*. 2003). The unit of TEC is given in TECU where 1 $\mathrm{TECU} = 10^{16}$ el/m^2. In statistics and information theory, symmetric Kullback–Leibler divergence (SKLD) is a widely used measure of distance between

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two probability density distributions (Cover and Thomas 2006). Previously, SKLD is applied to measure the difference between the experimental probability density functions (e-pdf) of average quiet day TEC (AQDT) and days prior to the earthquake, and it has been observed that GPS stations within 150–350 km to the epicentre demonstrate a significant variability nine to two days prior to the earthquake (Arikan *et al*. 2009, Karatay *et al*. 2009, Karatay 2010, Karatay *et al*. 2010a). According to the results of these studies, SKLD proved itself to be a better measure of disturbance or difference compared to cross correlation coefficient and L2-norm methods. Further, SKLD has been applied to earthquakes in North Anatolian Fault (NAF) using GPS recordings of Turkish National Permanent GPS Network (TNPGN) (Karatay 2010, Karatay *et al*. 2010b, 2010c, Özilhan 2010). Even with magnitude 4 or 5 earthquakes, close or on NAF, significant variability in TEC is observed using SKLD in comparisons with AQDT and consecutive days. In this study, the variability of Global Positioning Satellite-Total Electron Content (GPS-TEC) prior to 23 October 2011 earthquake in Van is investigated using SKLD in comparisons with AQDT and consecutive days.

2. Application of SKLD to detect TEC variability

In this section, we will summarize the SKLD measurement method (Karatay 2010, Karatay *et al*. 2010a, Özilhan 2010). Let

$$\mathrm{X}_{u;d} = [\mathrm{X}_{u;d}(1).....\mathrm{X}_{u;d}(n).....\mathrm{X}_{u;d}(N)]^T \tag{1}$$

represent the set of TEC data of length N estimated for day d and GPS station u. Here, n is the index where $1 \leq n \leq N$ and subscript T is the transpose operator. In order to compare TEC values obtained from different seasons and days, data vectors as in equation (1) are normalized. The experimental probability density function (e-pdf) of TEC for station u and day d can be approximated using the TEC estimates as:

$$\hat{\mathrm{P}}_{u;d} = \mathrm{X}_{u;d}\left[\sum_{n=N_i}^{N_x} x_{u;d}(n)\right]^{-1} \tag{2}$$

where N_i and N_s denote the initial and final indices for the measurement set, respectively. In order to compare the behaviour of TEC for the quiet days with those from the EQD, an AQDT estimate for each GPS station is obtained. For N_d quiet days for station u, AQDT is defined as:

$$\mathrm{X}_{u;d_\mathrm{i}-d_x} = \frac{1}{N_d}\sum_{n_d=d_i}^{d_x} \mathrm{X}_{u;n_d} \tag{3}$$

where n_d is the index for quiet day period (QDP) which extends from d_i to d_s. Approximation for the e-pdf of AQDT is defined as follows:

$$\hat{\mathrm{P}}_{u;d_i-d_x} = \mathrm{X}_{u;d_i-d_x}\left[\sum_{n=N_i}^{N_x} x_{u;d_i-d_x}(n)\right]^{-1} \tag{4}$$

The Kullback–Leibler (KL) divergences of normalized e-pdfs defined in equation (2) for day d between stations u and v can be defined as:

$$KL\left(\hat{\mathrm{P}}_{u;d} \backslash \hat{\mathrm{P}}_{v;d}\right) = \sum_{n=N_i}^{N_x} \hat{P}_{u;d}(n) 1\mathrm{n}\left(\frac{\hat{P}_{u;d}(n)}{\hat{P}_{v;d}(n)}\right) \tag{5}$$

$$KL\left(\hat{\mathrm{P}}_{v;d} \backslash \hat{\mathrm{P}}_{u;d}\right) = \sum_{n=N_i}^{N_x} \hat{P}_{u;d}(n) 1\mathrm{n}\left(\frac{\hat{P}_{v;d}(n)}{\hat{P}_{u;d}(n)}\right) \tag{6}$$

where $N_i < n < N_s$. The SKLD is defined as the sum of the KL divergences (Cover and Thomas 2006, Karatay 2010) as:

$$KLD\left(\hat{\mathrm{P}}_{u;d}; \hat{\mathrm{P}}_{v;d}\right) = KL\left(\hat{\mathrm{P}}_{u;d} \backslash \hat{\mathrm{P}}_{v;d}\right) + KL\left(\hat{\mathrm{P}}_{v;d} \backslash \hat{\mathrm{P}}_{u;d}\right) \tag{7}$$

Using normalized AQDT, for day d of station u, SKLD is defined as $KL\bar{D}\left(\hat{\mathrm{P}}_{u;d}; \hat{\mathrm{P}}_{u;d_i-d_x}\right)$. For consecutive days of station u, SKLD is defined as $KLD\left(\hat{\mathrm{P}}_{u;d}; \hat{\mathrm{P}}_{u;d+1}\right)$.

3. A summary of the 23 October 2011, Van Earthquake

According to Kandilli Observatory and Earthquake Research Institute (KOERI) of Bogazici University, National Earthquake Monitoring Center (NECM), an earthquake of magnitude Mw = 7.2 (ML = 6.6) took place on 23 October 2011 at 10:41 UT (Universal Time) in Eastern Turkey to the northeast of Lake Van approximately 30 km to the north of the city Van with a population of 380,000. The earthquake epicentre is located at (38.7578°N, 43.3602°E) with a depth of 5.0 km. The earthquake was felt within a 500 km radius and along the Iran–Turkey border region. The main shock has been followed by an intensive aftershock activity published at http://www.koeri.boun.edu.tr/scripts/lasteq.asp. The size of the largest aftershock recorded until present is ML = 5.7 on 23 October 2011 at 20:45 UT. The number of aftershocks above magnitude 3 has reached 307 as of 13:45 UT, 24 October 2011. Historically, Eastern Anatolia has suffered from severe earthquakes. The most recent one in the area occurred on 24 November 1976 at 12:22 UT, with Ms = 7.5 in Caldiran (39.05°N, 44.04°E), close to Van. In figure 1, the time series evolution of mura, a TNPGN station 43 km to the epicentre, is presented. The coseismic displacement due to the first shock is highly evident in north–south and east–west directions. In the following section, SKLD will be applied to TNPGN stations for 23 October 2011, Van earthquake.

4. Results

The possible seismic disturbances in the ionosphere due to the Van earthquake is investigated using the SKLD measure described in section 2. The Receiver INdependent EXchange (RINEX) data from GPS stations are obtained from the TNPGN. TNPGN is the reference station network of 146 continuously operating

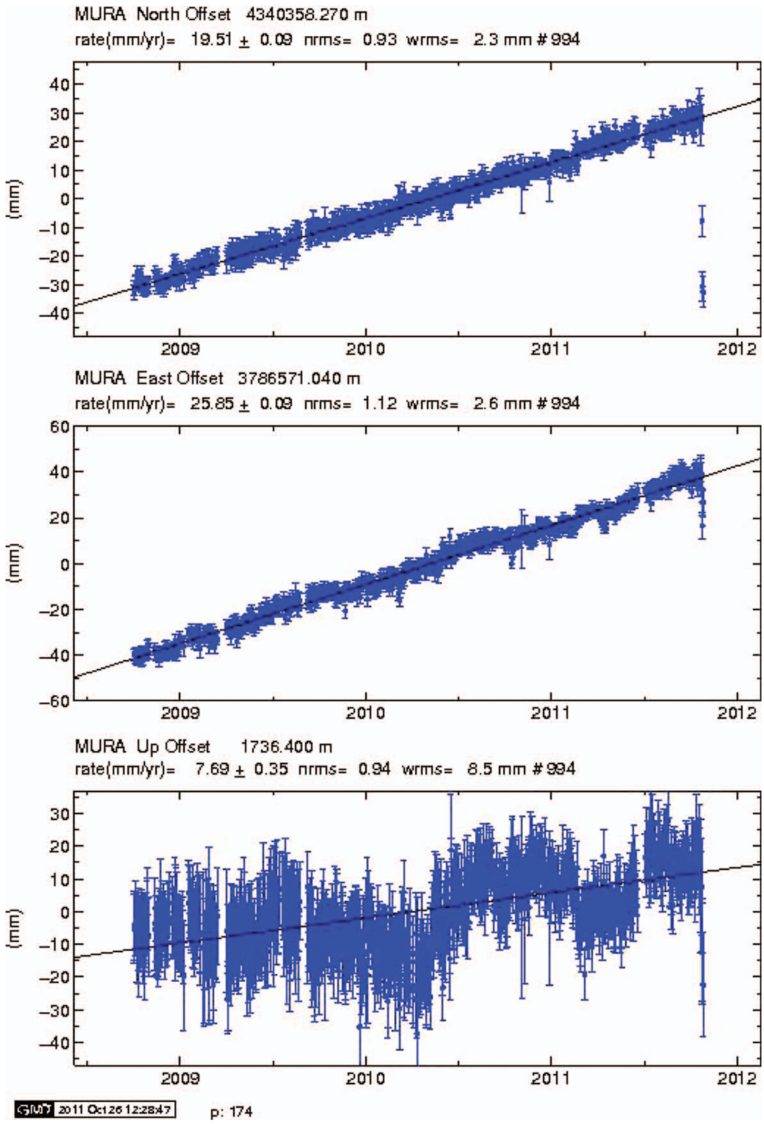

Figure 1. Survey mode observations and coseismic displacement due to the first shock for mura, 43 km to the epicentre.

GNSS stations (CORS) which are distributed uniformly across Turkey and North Cyprus Turkish Republic since May 2009. The GPS-TEC values for each station are estimated by IONOLAB-TEC using the Reg-Est algorithm described in Arikan *et al.* (2003) and Nayir *et al.* (2007), www.ionolab.org with a time resolution of 2.5 min. The missing values of TEC or SKLD in figures of this section are due to the lack of RINEX data for those stations and/or days.

AQDT is obtained using the IONOLAB-TEC in equation (4) from 25 to 28 March 2011. AQDT is compared with a magnetically QDP of 25–28 April 2011 and also with EQD, 14–23 October 2011. Quiet days are chosen according to the Kp and Dst indices provided in http://wdc.kugi.kyoto-u.ac.jp, and also there are no recorded earthquakes during those periods in Turkey. The geomagnetic disturbance indices of Kp and Dst indicate that the EQD period is also magnetically quiet. Therefore, we expect that the disturbances in the ionosphere to be due to seismic activities.

The 146 GPS stations in TNPGN are divided into five categories with respect to the distance to the epicentre. The first zone, Z1, includes stations which are within 150 km radius of the epicentre; Z2 includes stations which are 150–360 km to the epicentre; Z3 stations are within 360–550 km to the epicentre; Z4 zone includes stations within 550–780 km to the epicentre and finally, Z5 have stations whose distances to the epicentre is larger than 780 km. An AQDT is obtained for each of these stations and it is compared with QDP and EQD using SKLD. It is observed that for all the stations in the network, SKLD of EQD (*Se*) is significantly larger than SKLD of QDP (*Sq*), on 14 and 15 October 2011, eight and nine days prior to the earthquake. The difference ($D_u = Se_u - Sq_u$) for each station is computed and then an average is taken within the zone, D_m. In table 1, D_m is presented for five zones for both 14 and 15 October 2011. It is observed that eight and nine days before the earthquake with 7.2 magnitude, $D_u = Se_u - Sq_u$ values for all the stations in TNPGN network indicated a significant difference compared to the quiet days. The mean difference D_m is highest in the first two zones that are close to the epicentre. D_m reduces as the distance from the epicentre gets larger in zones Z3, Z4 and Z5. A comparison of SKLD of AQDT with QDP and EQD is also provided for four stations in figure 2. In figure 2, Se_u and mean Sq_u values of mura, surf, klis and yenc are provided. The mura station is 43 km, surf is 435 km, klis is 596 km and yenc is 1,394 km from the epicentre. The yenc station is located on the western edge of NAF. The difference $D_u = Se_u - Sq_u$ is significant for all stations either 43 km or 1,394 km from the epicentre. In figure 3, IONOLAB-TEC values are presented for mura for 23 October 2011 (earthquake day, dotted line), 15 October 2011 (eight days prior to the earthquake, solid line), 26 April 2011 (quiet day, dashed line) and AQDT (dash dot line). The significant increase in ionization levels is apparent starting from nine days prior to the earthquake, compared to AQDT and quiet day TEC. Eight days prior to the earthquake, TEC has the same level for the night hours and there is an increase in peak TEC for the day hours. Yet, on earthquake day, the ionization is very high even during night hours. Also, the uncharacteristic increase in figure 3 for earthquake day between 16:00 UT and 22:00 UT might be due to other effects. SKLD is also applied to find the difference of TEC between consecutive days, $KLD(\hat{\mathrm{P}}_{u;d}; \hat{\mathrm{P}}_{u;d+1})$. For each station starting with nine days prior to the earthquake, SKLD of consecutive days Ke_u are computed. Similarly, SKLD of consecutive days are computed for days in QDP as Kq_u. In figure 4, Ke_u and mean of Kq_u are presented for four stations, namely mura, surf, klis and yenc. The SKLD are indicated for the first day for a day 1 and day 2 comparison. For example, the

Table 1. *Dm*, mean of the differences $D = Se - Sq$ within a distance zone.

Zone	D_m for 14 October 2011	D_m for 15 October 2011
Z1	0.0452	0.0461
Z2	0.0333	0.0517
Z3	0.0245	0.0439
Z4	0.0247	0.0351
Z5	0.0233	0.0205

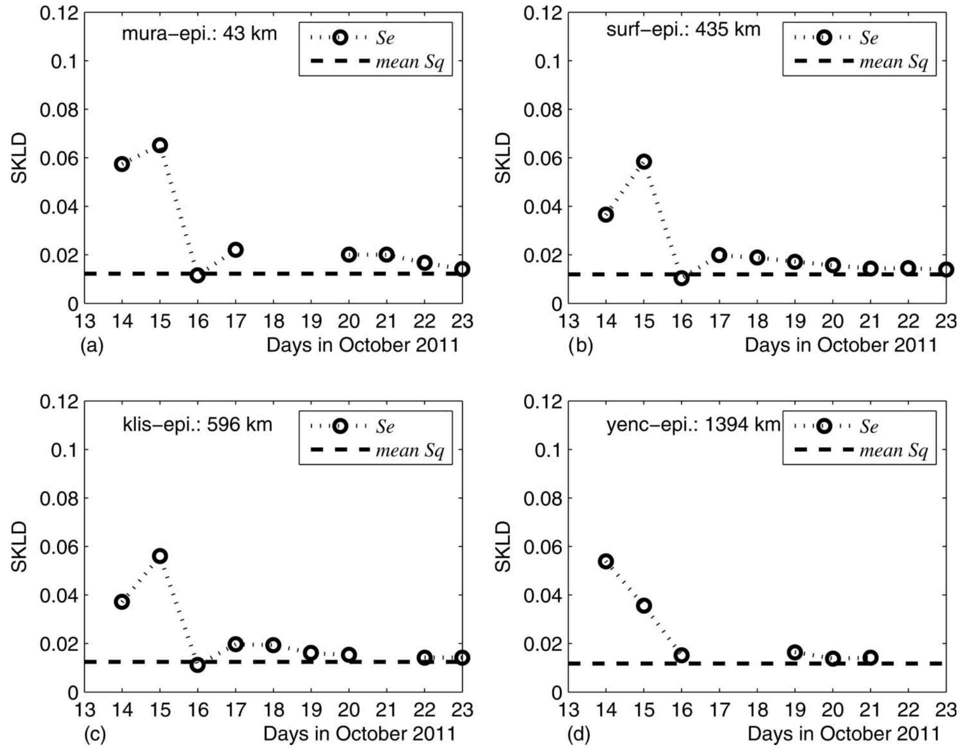

Figure 2. Comparison of SKLD values of *Se* (AQDT with EQD) and mean of *Sq* (AQDT with QDP) (a) mura, (b) surf, (c) klis and (d) yenc.

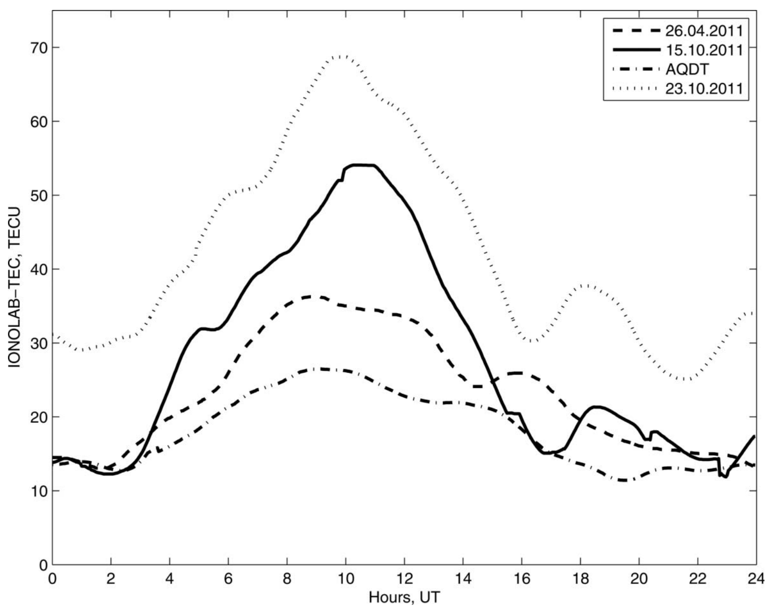

Figure 3. IONOLAB-TEC values for mura on 23 October 2011 (earthquake day, dotted line), 15 October 2011 (eight days prior to the earthquake, solid line), 26 April 2011 (quiet day, dashed line) and AQDT (dash dot line).

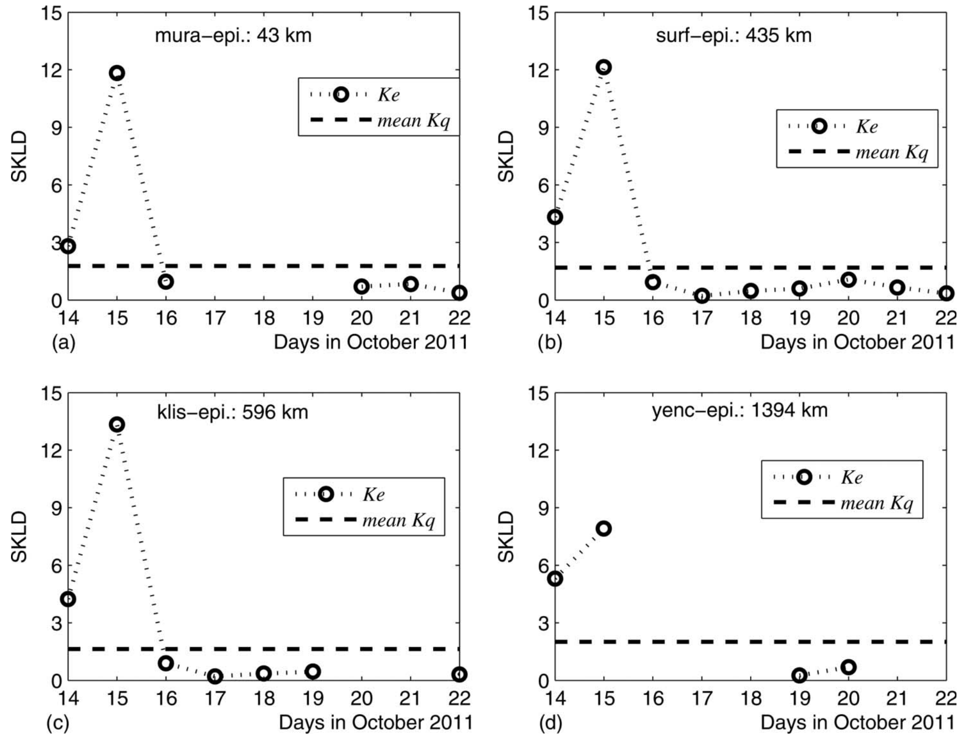

Figure 4. Comparison of SKLD values of consecutive days: *Ke* (EQD) and mean of *Kq* (QDP) for (a) mura, (b) surf, (c) klis and (d) yenc. The SKLD are indicated for the first day for a day 1 and day 2 comparison. For example, the comparison of 14 and 15 October is plotted for 14 October.

comparison of 14 and 15 October is plotted for 14 October and the comparison of 22 and 23 October is plotted for 22 October. It is observed that there is a major difference in consecutive EQD nine and eight days prior to the earthquake.

5. Conclusions

In this study, initial results for a possible the coupling of seismic activity to the ionosphere are presented for 7.2 magnitude earthquake in Van, Turkey that occurred on 23 October 2011. The variability of GPS-TEC between EQD and quiet days, and also between consecutive days prior to the earthquake is investigated using SKLD. In previous studies, for comparison between AQDT and EQD for earthquakes with magnitudes 4 and 5 on NAF, it is observed that SKLD is a strong candidate for developing an earthquake precursor tool for the stations that are located less than 150 km from the earthquake zones. In Van earthquake with magnitude 7.2, even stations 1,394 km from the epicentre on the NAF deviated significantly from the quiet day threshold. In the comparison of the consecutive days for each station, similar results are obtained. These initial results demonstrate that SKLD can be developed into a precursor tool for distinguishing seismic activity with a long-term constant analysis. Detailed geodetic analysis of displacement of GPS stations in TNPGN for Van earthquake is prepared by General Command of Mapping. For future studies, the earthquake precursor signal has to be identified as residuals in a local area over a known fault zone with a dense GPS receiver grid. Observation space, probabilistic transition mechanism and the thresholds will be formed with constant monitoring.

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